J. Crash Analysis of Adhesively-Bonded Structures (CAABS)

Principal Investigator: J. Michael Starbuck
Oak Ridge National Laboratory
P.O. Box 2009, Oak Ridge, TN 37831-8048
(865) 576-3633; fax: (865) 574-8257; e-mail: starbuckjm@ornl.gov

ACC Collaboration Contact: Naveen Rastogi
Visteon Corporation
6100 Mercury Drive, #SW61-025, Dearborn, MI 48126
(313) 755-6264; fax: (313) 755-4229; e-mail: nrastogi@visteon.com

Project Manager, Composites: C. David Warren
Oak Ridge National Laboratory
P.O. Box 2008, Oak Ridge, TN 37831-6065
(865) 574-9693; fax: (865) 576-4963; e-mail: warrencd@ornl.gov

Technology Area Development Manager: Joseph A. Carpenter
(202) 586-1022; fax: (202) 586-1600; e-mail: joseph.carpenter@ee.doe.gov
Field Technical Manager: Philip S. Sklad
(865) 574-5069; fax: (865) 576-4963; e-mail: skladps@ornl.gov

---

Contractor: Oak Ridge National Laboratory
Contract No.: DE-AC05-00OR22725

Objectives

- Develop a comprehensive experimental and analytical methodology to analyze and design adhesively-bonded automotive composite structures to sustain axial, off-axis, and lateral crash/impact loads.
- Determine the rate sensitivity of bonded tubes to crush through experiments on the Oak Ridge National Laboratory (ORNL) Test Machine for Automotive Crashworthiness (TMAC).
- Determine influence of critical joint design parameters, for example, bond length, bond thickness, and fillet, on specific energy absorption.
- Experimentally determine the full-field deformations at joint discontinuities for validation of analytical/numerical results.

Approach

- Coordinate with the bonded-joint experimental and analytical efforts undertaken in the Automotive Composites Consortium (ACC) thrust “Composite Crash Energy Management” (report 4.I)
- Select a substrate, adhesive, and representative subcomponent joint geometry for evaluation.
- Characterize substrate material, adhesive material, and coupon-level joints under static and dynamic loads.
- Build and test unbonded and bonded rail components under static and dynamic crush loads.
- Correlate experimental results with analytical results by developing finite-element-based tools with appropriate material models and progressive-damage algorithms.
- Enhance the understanding of joint performance by conducting full-field deformation measurements.

Accomplishments

- Characterized tensile and fracture toughness of bulk adhesive at quasi-static and dynamic loading rates.
- Completed scanning electron microscopy (SEM) studies to characterize the fracture surface in bulk adhesive compact-tension specimens.
- Characterized static and dynamic behavior of the braided carbon-fiber composite substrate under uniaxial tension loads.
- Completed static and dynamic tests at three different velocities on both unbonded and bonded tubes using TMAC.
- Designed and fabricated a slack adapter for conducting dynamic coupon-level tests.
- Completed static and dynamic tests on specimens having single-lap and double-notch joint geometries to determine influence of critical joint design parameters on specific energy absorption.
- Completed static and dynamic Mode I fracture toughness tests using the double-cantilever-beam (DCB) driven-wedge test.
- Procured new high-rate equipment for conducting coupon-level dynamic tests at higher rates than current equipment capability.

Future Direction

- Complete dynamic testing of substrate, bulk adhesive, and coupon-level joints at rates greater than 1 meter/second.
- Complete Mode II, Mode III, and mixed-mode fracture toughness tests at static and dynamic rates.
- Complete bonded and unbonded tube tests at two additional velocities.
- Install and set-up test equipment for characterizing full-field deformation patterns in adhesive joints.

Introduction

The objective of this project is to develop a comprehensive experimental and analytical methodology to analyze and design adhesively-bonded automotive composite structures to sustain axial, off-axis, and lateral crash loads. This direct-funded project will be closely aligned with the experimental and analytical efforts undertaken by the Automotive Composites Consortium (ACC) "Composite Crash Energy Management" thrust (see report 4.I). The focus of this work, however, will be restricted to the adhesive-joint related issues. The key to the methodology development is the understanding of how critical joint design parameters, for example, bond length, bond thickness, and fillet, affect the energy absorption. Recent investigations at ORNL have provided valuable insight toward the understanding of composite joint performance and composite crashworthiness. The next logical step is determining the correlation between measurable adhesive joint parameters and their influence on the structure to dissipate energy and ultimately predict crashworthiness for a particular composite design.

Experimental tasks include material testing under quasi-static and dynamic loads for substrates, adhesives, and joints; full-field deformation mapping of joints for correlation with computational results; strain-rate sensitivity studies; fracture toughness testing; and test method development as required. These experimental results will provide the building blocks for model developments—first at the coupon level, then progressing in complexity to component level. Correlation with experimental results will provide the basis for which the analytical developments, including development of constitutive laws, materials models, damage algorithms, and new finite elements will be made. Structural tests will be conducted on the new intermediate-rate Test Machine for Automotive Crashworthiness (TMAC)] at ORNL.

Approach and Results

The technical approach involves both experimental and analytical tasks. There are four main tasks:

Task 1—Materials Selection and Screening,
Task 2—Material Characterization,
Task 3—Component Testing, and
Task 4—Computational Tools Development.

Task 1 was completed and reported on in the FY 2002 annual report. The chopped-carbon-fiber prepreg material system selected was characterized from flat plaques provided by the vendor. Discussions with the vendor led to an overly optimistic view of the suitability of the material for this project. Additionally, delays in receipt of the material from the supplier resulted in consideration of a carbon-fiber sheet-molding-component (SMC). Both materials were unsatisfactory due to processing difficultly and material variability. As a result of the variability in the initial material screening tests and difficulty in fabricating tubes with this material, the substrate material was changed to a carbon-fiber braided system. The woven-fabric prepreg is comprised of T300B carbon fiber with a tow size of 3K and 42% (by weight) epoxy resin.

Task 2 was initiated during FY 2002 and has continued through FY 2005. This task focuses on determining the rate dependencies, if any, for mechanical properties of the bulk adhesive, substrate, and coupon-level joints.

Task 3 started in FY 2004 with preliminary tests to determine if the selected composite-tube geometry would provide for a stable progressive crush behavior instead of global buckling. The geometry for the tube was 100 mm by 100 mm square with a 3 mm wall thickness and a 300 mm length. A 45-degree bevel was used for the triggering mechanism. These tests showed that a progressive crush failure mechanism was achievable using this geometry. Therefore, the required unbonded and bonded tubes needed for the remainder of the project were procured from Pacific Composites.
In Task 4, the development of computational tools was subcontracted to Virginia Tech under ACC Cooperative Agreement funding.

Bulk Adhesive Specimen Fabrication

The adhesive used, PL731SI, is a commercially available, two-part epoxy system produced by Sovereign Specialty Adhesives Inc. (Chicago, IL). The bulk adhesive testing consisted of tension, compression, shear, and fracture toughness. In addition, differential scanning calorimetry and dynamic mechanical analysis tests were conducted to verify the degree of cure. The key to this task was the successful fabrication of high-quality specimens (e.g., low void content) to accurately quantify the bulk adhesive mechanical properties. The resin and hardener were mixed at a 4:1 ratio using a MixPac MC 10-24 static mixer on a Profill pneumatic dispenser. The adhesive was degassed by centrifuging for 15 minutes at room temperature in a container that could serve as a syringe for subsequent dispensing. The compression and shear testing were accomplished using cylindrical-rod specimen geometries. Cylindrical-rod specimens were fabricated using centrifugation and glass test tubes as molds. Initial difficulties in producing flat plaques were alleviated by developing a mold-filling process that uses an adequate supply of excess adhesive under pressure to back-fill the mold cavity. The adhesive was carefully squeezed onto a stainless steel plate that had been coated with Lilly RAM 225 mold release to allow for subsequent separation. A dam of silicone rubber tubing and rigid spacers of the desired thickness were used to support a second plate to produce a plaque with consistent thickness. The plates were clamped together and the assembly was held at 125ºC for 60 minutes in a convection oven. The curing procedure was used based on discussions with the manufacturer. Using this technique, neat adhesive plaques were prepared with thicknesses of 8 and 27 mm. High-quality specimens for all bulk adhesive tests were fabricated with these two approaches.

Bulk Adhesive Fracture Toughness

A key parameter in the development of computational models under Task 4 was the rate-sensitive fracture toughness of the bulk adhesive. Miniature compact tension specimens were machined from hockey-puck-shaped adhesive castings. The castings were fabricated with zero voids using the techniques developed for flat plaques and cylindrical rods. Quasi-static and dynamic fracture toughness tests were conducted on the bulk adhesive using an 8-mm-thick specimen per the geometry specified in ASTM D5045.

Fracture toughness tests of the bulk adhesive were conducted at room temperature on a conventional, closed-loop, servo-hydraulic machine at rates ranging from 10^{-6} to 1 m/s. The load frame was equipped with a commercial slack adaptor or lost-motion device. Checkout tests were completed and it was determined that the target velocities could be achieved prior to the load application. However, at rates of 0.5 and 1 m/sec, it was difficult to accurately detect the relatively small loads generated by the test specimen because of contributions from the momentum of the 4-kg commercial slack adapter. Hence, a much smaller and lighter slack adapter shown in Figure 1 was fabricated in-house by cutting and threading a #2 Morse taper [Standard Extension Drill Socket:1-5161-015]. Fracture toughness tests were successfully repeated at various rates from 10^{-6} to 1 m/sec with three specimens tested at each rate. The new setup, shown in Figure 2, included a smaller load cell, a shorter and simplified load train between the load cell and specimen, and reduced weight on the specimen because of the lighter adapter.

Figure 3 illustrates the fracture toughness over the range of loading rates from 10^{-6} to 1 m/s. Fracture toughness was found to decrease as a function of loading rate, resulting in a drop in fracture toughness at 1 m/sec to about 20% of the value at lower rates. Error bars, which have been included in the figure, show that the data obtained was quite consistent at each condition. While the plane-strain

Figure 1. Small slack adaptor.

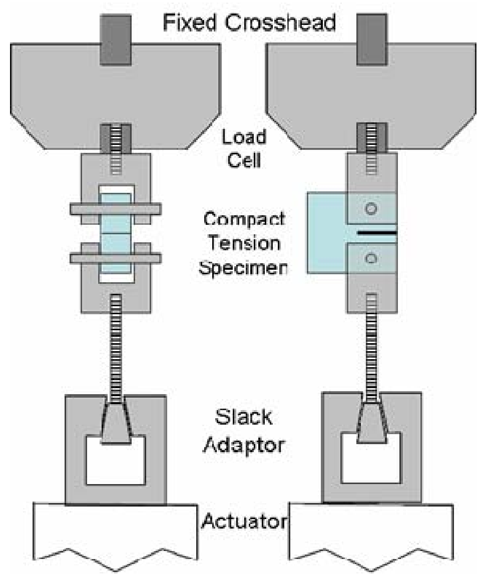

Figure 2. Load train.

fracture toughness, K_{Ic}, was determined from the intercept of a 95% slope with the load trace for the slower rates, the peak load was used to determine the fracture toughness at the higher rates. The dashed line in Figure 3 illustrates fracture-toughness values obtained from using the peak load values at the slower rates.

Figure 4 shows that at the lower rates there was extensive stress whitening and stable crack growth. Stress whitening was significantly reduced at higher testing speeds suggesting that plastic deformation at the crack tip was severely limited at the higher loading rates. Additionally, the failure appeared much more brittle at higher rates.

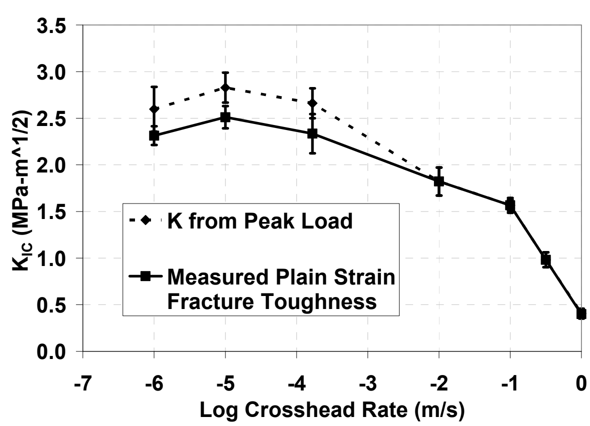

Figure 3. Measured fracture toughness values as a function of crosshead rate.

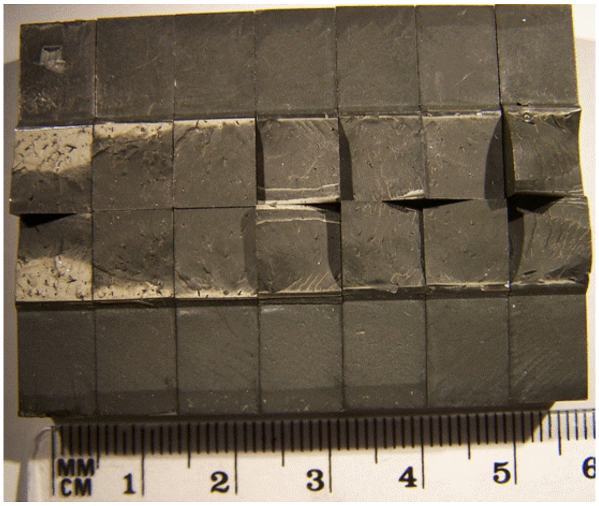

Figure 4. Illustration of typical stress whitening extent for range of crosshead rates in increasing order from left to right.

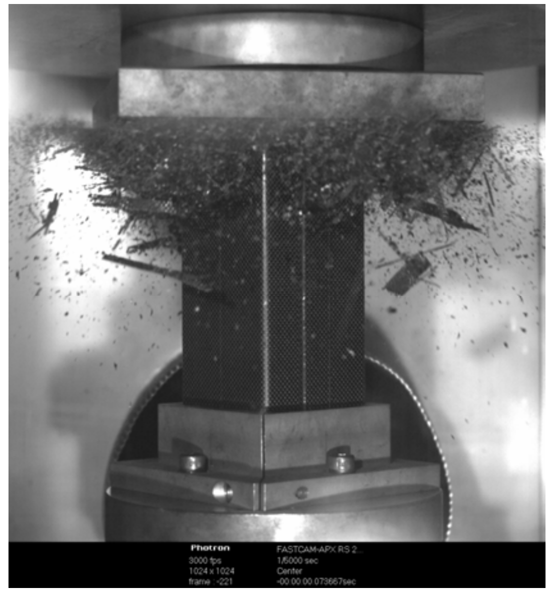

Figure 6. Bonded tube tested at 5000 mm/sec.

Bonded and Unbonded Tube Tests

The matrix for the tube testing consisted of crushing tubes having different bond widths and bond thicknesses at different velocities. The test velocities were chosen to be 50 mm/sec, 500 mm/sec, and 5000 mm/sec. The bond line thicknesses were either 0.5 mm or 1.0 mm and the bond width or tube overlap was either 25 mm or 50 mm. Figure 5 shows the test results in terms of the specific energy absorbed (SEA) as a function of test velocity. A snapshot of one of the bonded tubes being crushed at 5000 mm/sec is shown in Figure 6. The results in Figure 5 show a significant decrease in SEA as a function of loading rate with the largest reduction seen to occur above the 500 mm/sec rate.

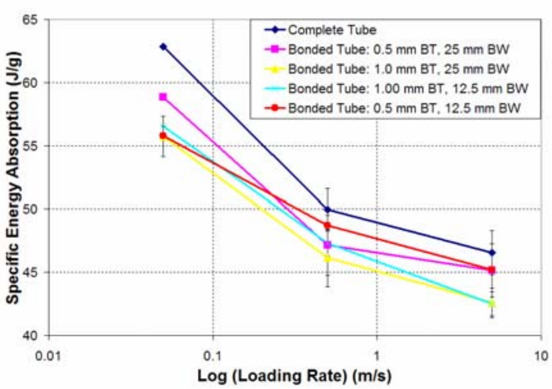

Figure 5. Measured tube SEA as a function of crosshead rate.

Also, the unbonded or complete tubes are seen to have the highest SEA compared to the bonded tubes. The effect of bond width appears to be negligible but there does appear to be a slight effect on bond thickness with the thinner bonds having slightly higher SEAs.

Conclusions

Material characterization tests were completed on bulk adhesive specimens and carbon-fiber woven-fabric substrate specimens. A key parameter for the modeling efforts being conducted at Virginia Tech was the determination of the rate-sensitive fracture toughness for the bulk adhesive. This was accomplished for Mode I by conducting compact-tension tests at different loading rates. The results showed a definite decrease in fracture toughness as the loading rate increased. The Mode I toughness at 1 meter/second was only 20% of the static value. Adhesive-joint specimens are currently being tested to characterize the rate sensitivities for Mode II fracture toughness.

To validate analytical models and to quantify the effect that an adhesive joint has on specific energy absorption, a series of progressive crush tests on composite tubes was conducted using TMAC. Tests on bonded and unbonded tubes were completed at loading rates of 50, 500, and 5000 mm/sec. The SEA's were calculated and the results showed a decrease in SEA with loading rate for both the unbonded and bonded tubes. This trend is similar to that seen in previous ACC composite tube crush data, where the majority of the decrease in SEA appears to occur below the 500 mm/sec velocity. Additional tube tests are planned to better quantify this effect.

Presentations/Publications/Patents

"Dynamic Testing for Quantifying Rate Sensitivities in Bonded Composite Structures," presented at the 2005 Society for Experimental Mechanics Annual Conference on Experimental and Applied Mechanics, June 7-9, 2005, Portland, Oregon. This paper was given the best paper award in the Advanced Composite Materials and System Track.

"Rate Dependent Cohesive Zone Modeling of Unstable Crack Growth in an Epoxy Adhesive," published in the Proceedings of the 2005 ASME International Mechanical Engineering Congress and Exposition.